Fundamental Concepts and Performance Measures in RF Transceiver Design

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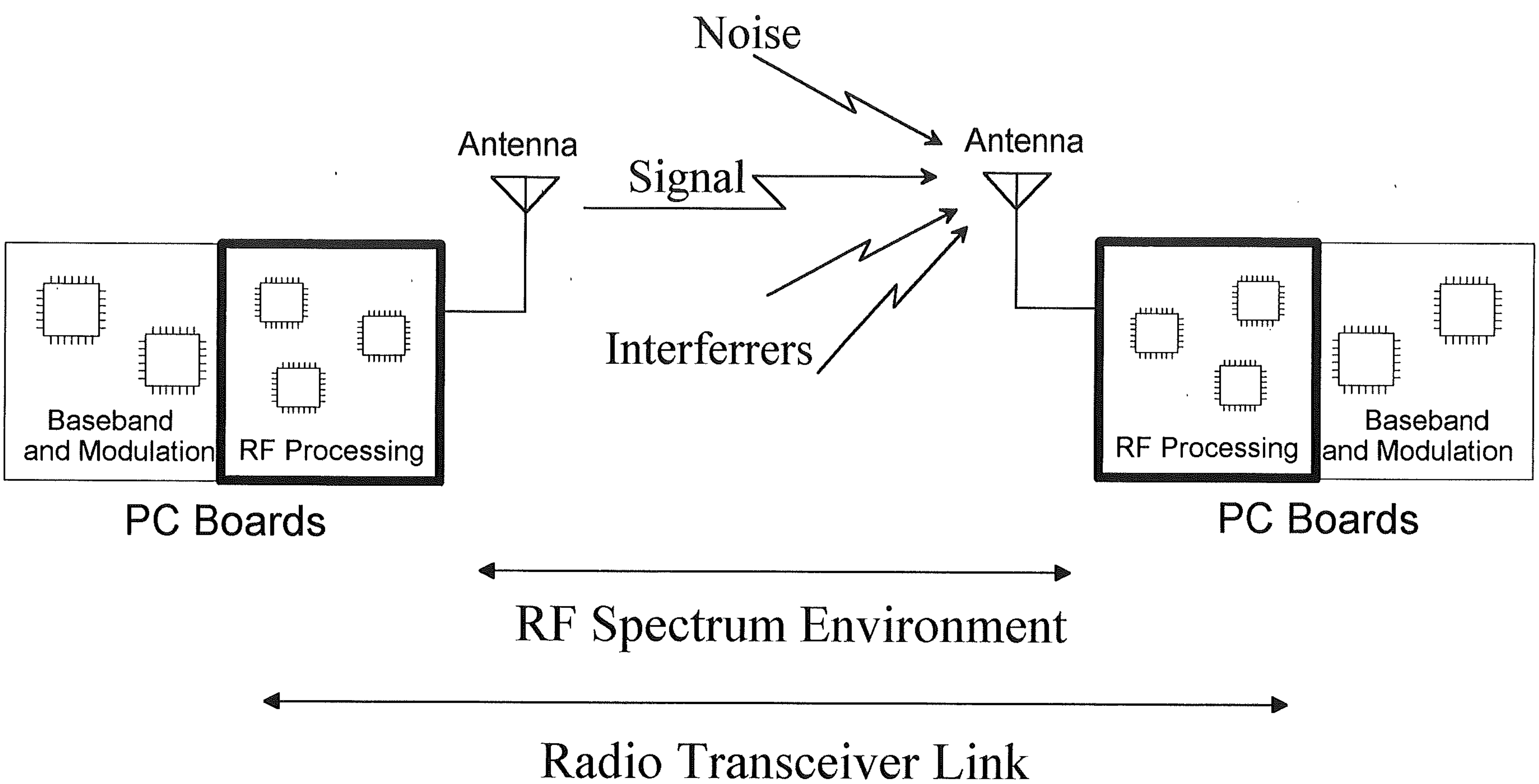
RFICs in the System Context



Topic Outline

- Fundamental Concepts
- Receiver Performance Measures
- Transmitter Performance Measures

Fundamental Concepts in RF Transceiver Design

- Radio Waves and Antennas
- Voltage, Power, and Impedance Levels
- Noise and Limits to Receiver Sensitivity

Radio Waves

Maxwell's Equations (source free):

$$Curl\ E = -\frac{\partial B}{\partial t}$$

$$Curl\ H = \frac{\partial D}{\partial t}$$

$$B = \mu H \quad D = \varepsilon E$$

=>

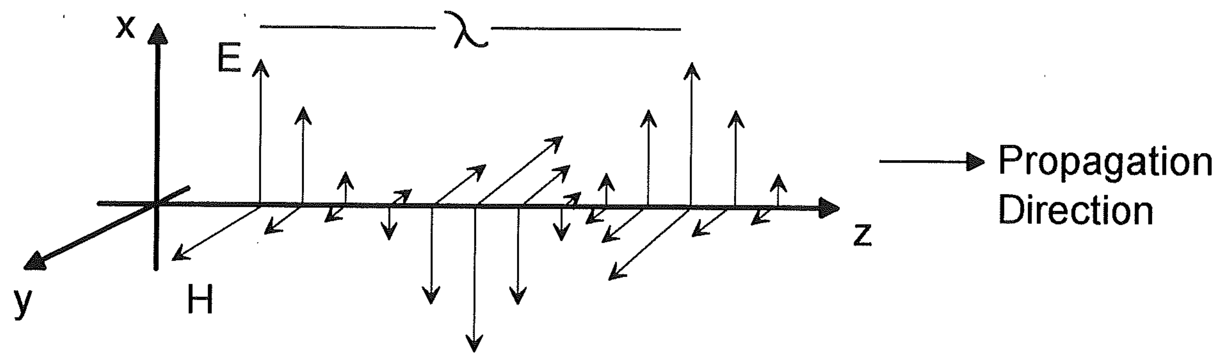
Plane Wave Solution:

$$E = E_x(z)\cos\left(\omega_o\left(t - \tfrac{z}{v_p}\right)\right)$$

$$H = H_y(z)\cos\left(\omega_o\left(t - \tfrac{z}{v_p}\right)\right)$$

where v_p = velocity of propagation

Snapshot of Field Intensity



Wavelengths

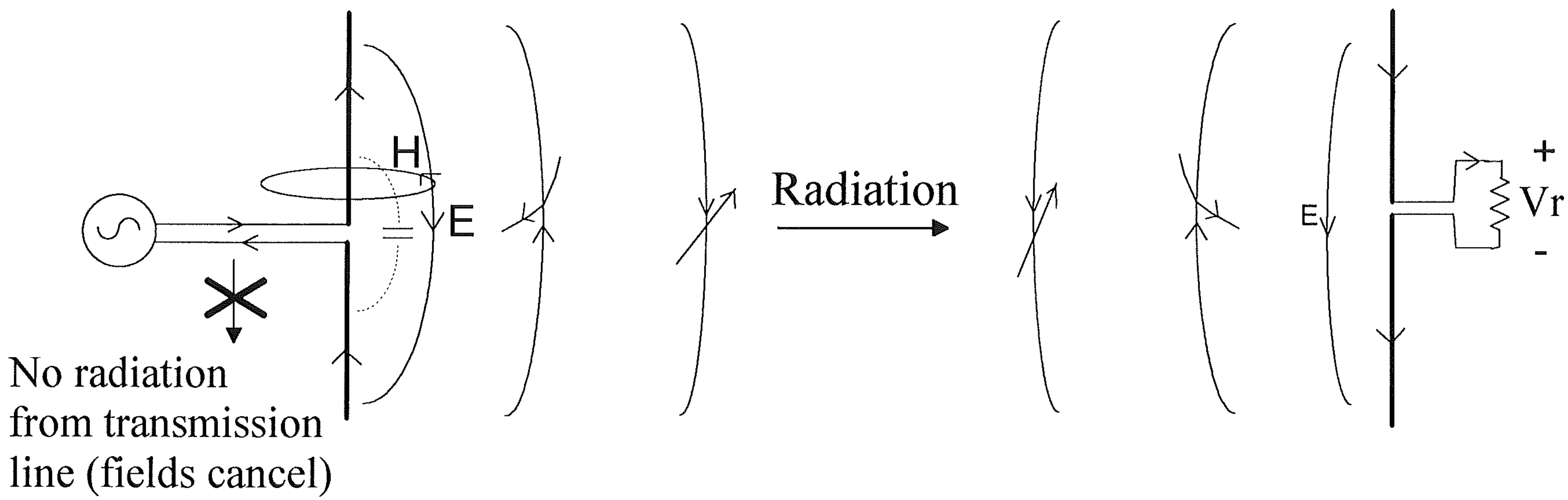
$$\lambda = \frac{v_p}{f}$$

$$v_p = \frac{1}{\sqrt{\mu\varepsilon}}$$

$v_p = c = 2.997E8$ m/s in free space

Frequency	Wavelength
1 kHz	300 km
1 MHz	300 m
1 GHz	0.3 m

Generation and Reception of Radio Waves

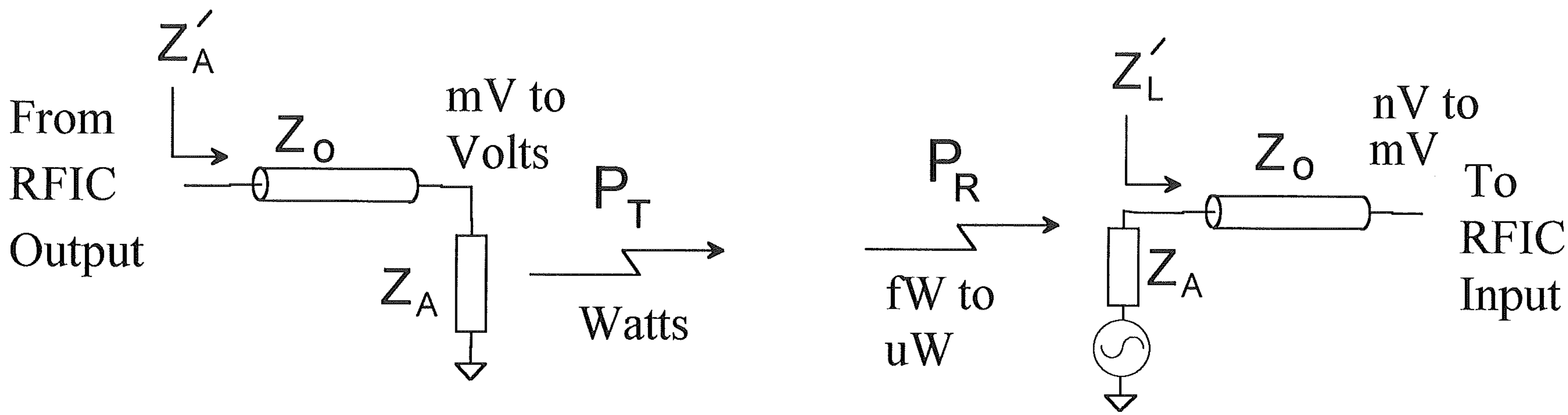


Voltage Source sets up currents in tx antenna

Currents Launch E and H Fields

Fields induce voltage/current in rx antenna

RFIC Circuit Designer's View



NOTES:

Transmit antenna acts as an impedance Z_A
Receive antenna acts as a voltage source with Thevenin impedance Z_A

Transmission lines (and PC board traces, bondwires, lead-frames, etc) transform impedances at RF except under special situations.

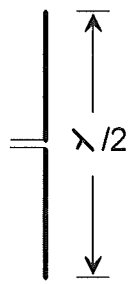
No impedance transformation if line impedance Zo matches load Z
Zo=50 Ohms is most common

Consider Z transformations if length > wavelength/100 (3mm @1 GHz)

Typical Antenna Size and Impedance

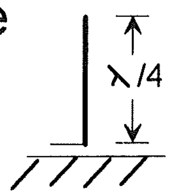
Resonant Antennas

Dipole



= 73+j0

Monopole

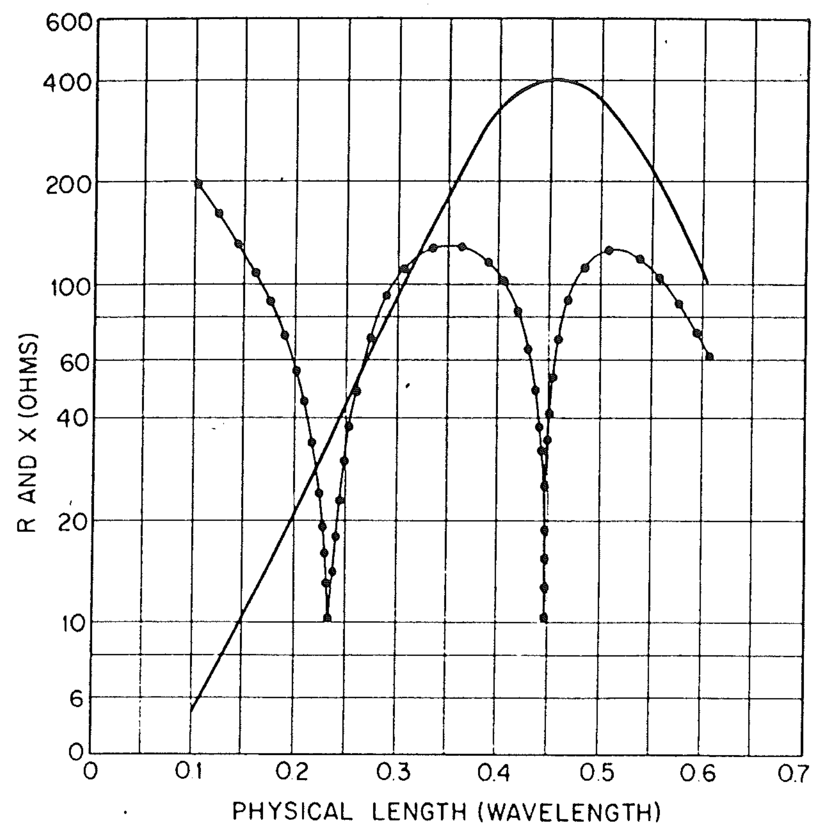


= 36+j0

Commercial

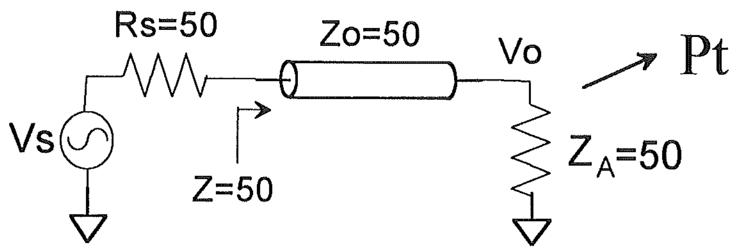
Various Shapes = 50+j0

Non-Resonant Antennas

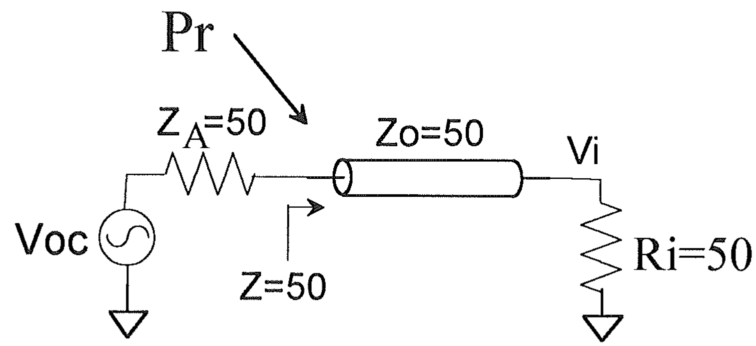


From American Radio Relay League Handbook, 1991.

50 Ohm Systems



TX Output — Tr Line — Antenna



Antenna — Tr Line — RX Input

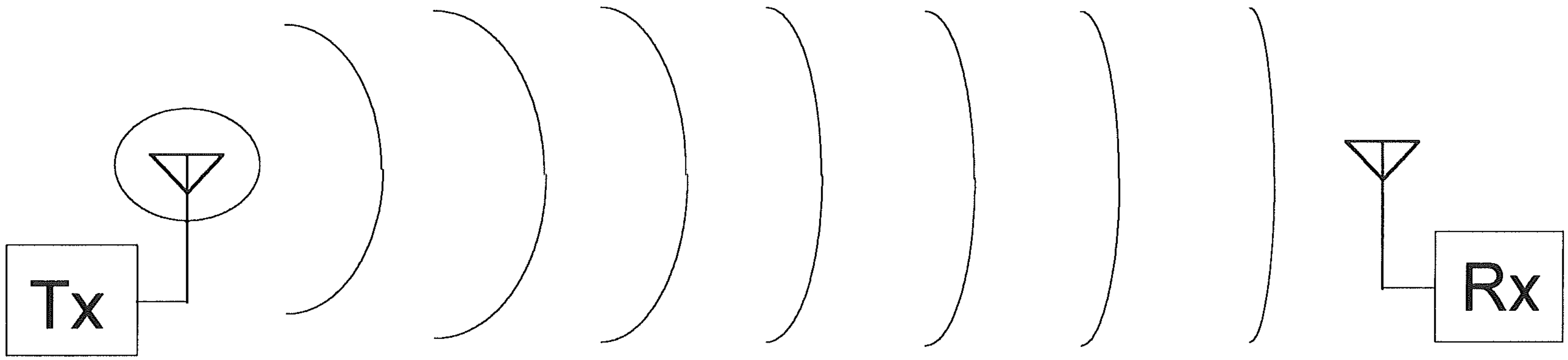
$$Vo = 1/2\ Vs$$

$$Pt = \frac{Vo^2}{50}$$

$$Vi = 1/2\ Voc$$

$$Pr = \frac{Vi^2}{50}$$

Representative Voltage and Powers



Transmitted Power and Voltages in 50 Ohm Systems

Application	Pout	Vout
Cordless	1mW	0.22
SS Cordless	0.1W	2.23
Cellular	0.6W	5.48
Base	10W	22.4

Simplified Link Equations

$$P_{density} = \frac{Pt\,Gt}{4\pi R^n}$$

$$P_{rcvd} = P_{density}\,A_{eff}$$

where G_t= antenna gain, n= 2 (free space) to 4, and A_{eff} =effective area of antenna($A_{eff} \sim \frac{\lambda^2}{4}$) for dipole

Received Power and Voltages in 50 Ohm Systems

Prcvd	Vrcvd
1 fW	224 nV
1 pW	7.07 uV
1 nW	224 uV
1 uW	7.07mV

Power in dBm and dBW

$$P_{dBW} \equiv 10\log(P)$$

$$P_{dBm} \equiv 10\log(\frac{P}{1mW})$$

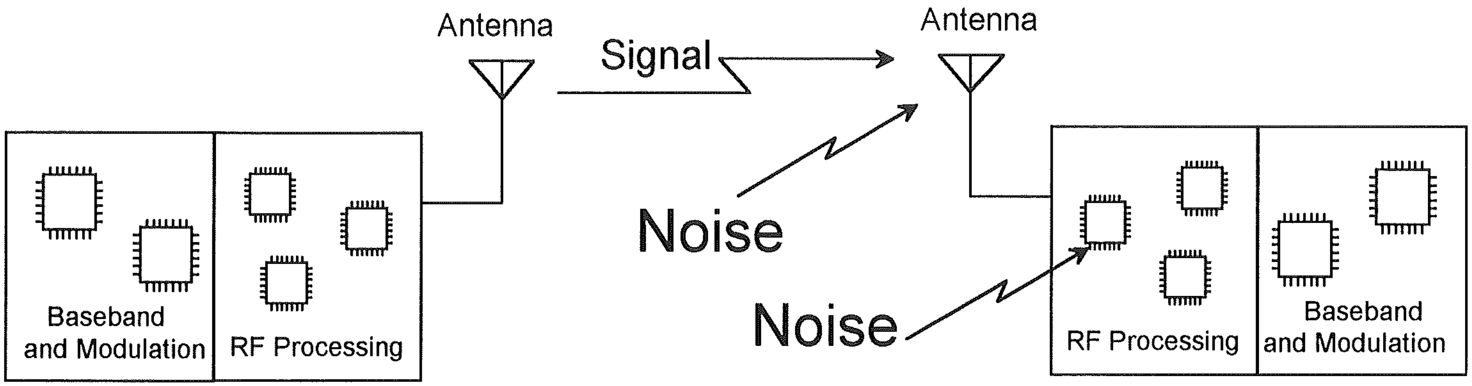
Example Transmitted Powers in dBW and dBm

Ptx	P_{dBW}	P_{dBm}
1 mW	-30	0
100 mW	-10	20
10 W	10	40 50

Example Received Powers in dBm

P_{rcvd}	P_{dBm}
1 fW	-120
1 pW	-90
1 nW	-60
1 uW	-30

Noise in Communication Systems



Sources of Noise: Antenna Noise $P_n = k\, T_A\, B$

Circuit Noise $i_n^2 = 4\, k\, T\, B\, \frac{1}{R}$ or $i_n^2 = 2\, q\, I_{DC}\, B$

where: k = Boltzmann's constant (1.38E-23 J/K) B = Bandwidth in Hz

q = Electronic charge (1.602E-19C) and T is in Kelvin (typically 290K)

NOTE: Best possible sensitivity of receiver is: $(k\, T_A\, B)(F)(S/N_{min})$
where B is signal bandwidth, F is noise figure of receiver,
and S/N_{min} is minimum acceptable S/N at demod.

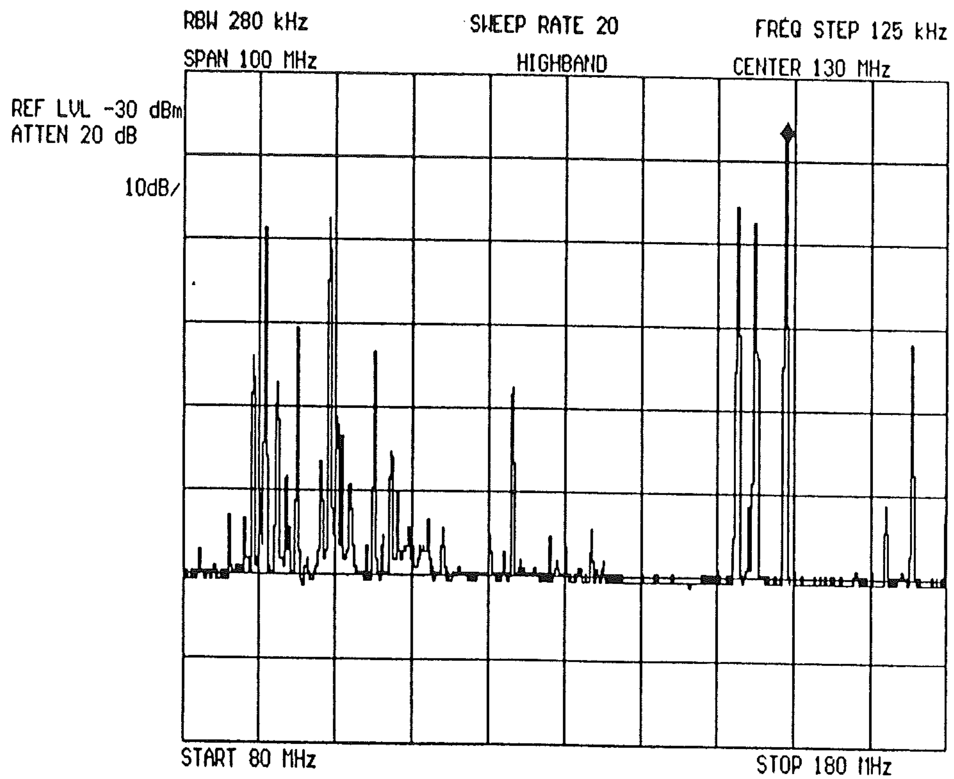
in dBm: Sensitivity = -174 + 10 log(B) + NF + C/N_{min} (if T_A = 290K)

Receiver Performance

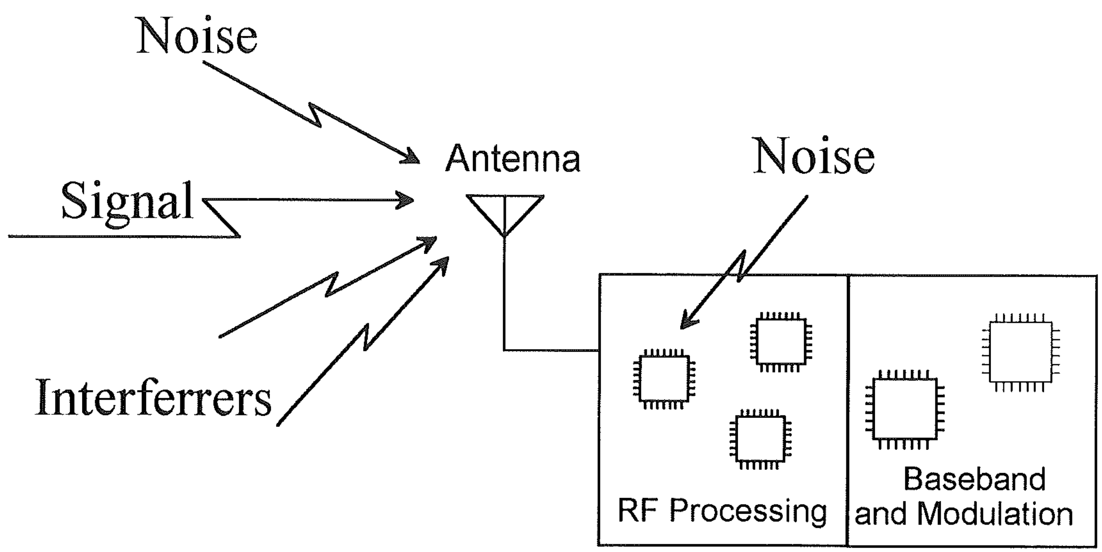
- The Spectrum Environment
- Selectivity and Image Rejection
- Weak Signal Performance
- Strong Signal Performance
- Dynamic Range and Power Consumption
- Example System Design

The RF Spectrum Environment

Spectrum in Surburban Area (80 MHz to 180 MHz)
Reference Level = -30 dBm   Vertical Scale = 10 dB per Division



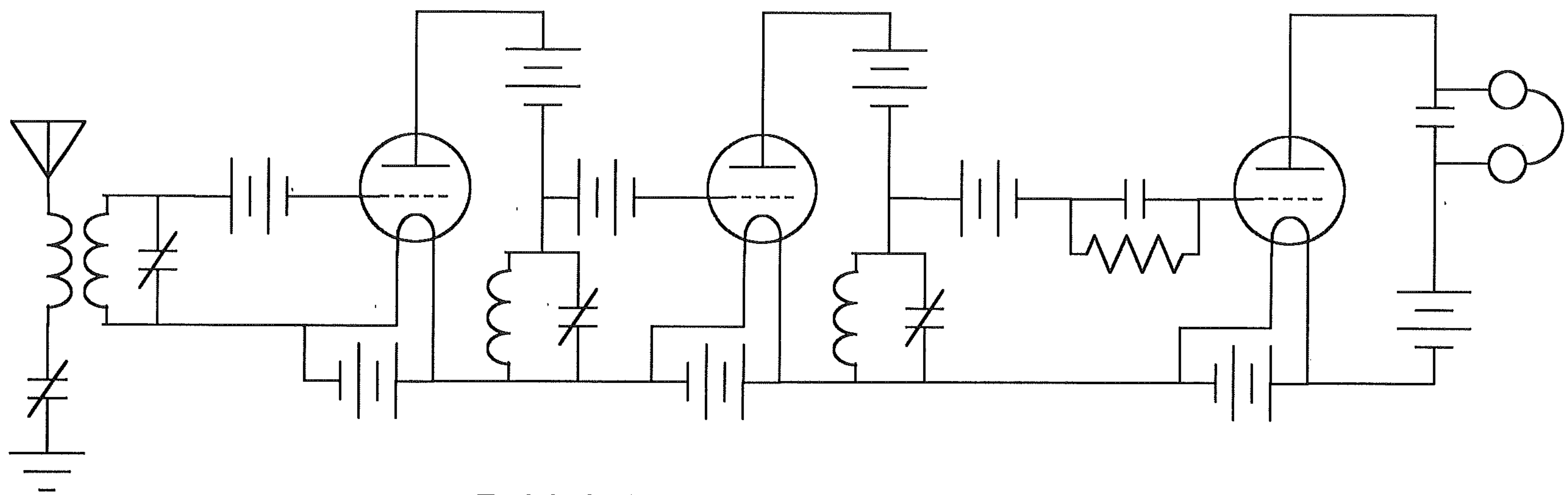
Basic Design Requirements



Design Requirements:

Amplify (weak) desired signal
Filter out interferrers
Minimize internally generated noise
Limit bandwidth to maximize S/N and sensitivity
Demodulate signal

Early Tuned-RF Receiver

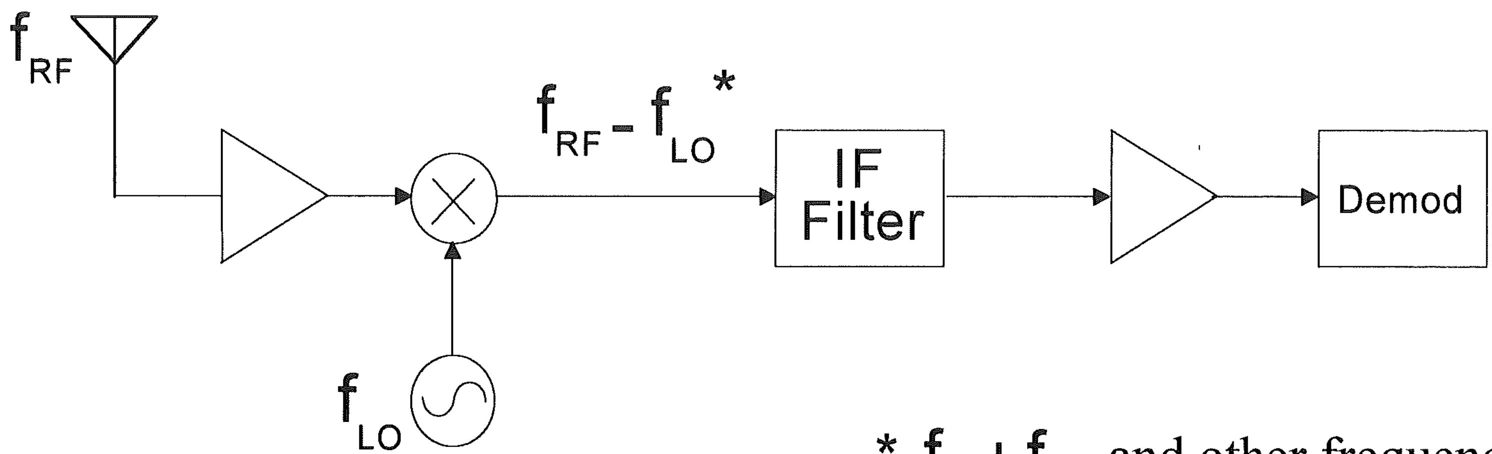


British Patent No. 147,147

Problems:

- All amplification at RF -> gain & stability problems
- Filters must be retuned when changing channels
- Limited selectivity

Armstrong's Heterodyne Design



* $f_{RF} + f_{LO}$ and other frequencies also, but filtered out

Advantages

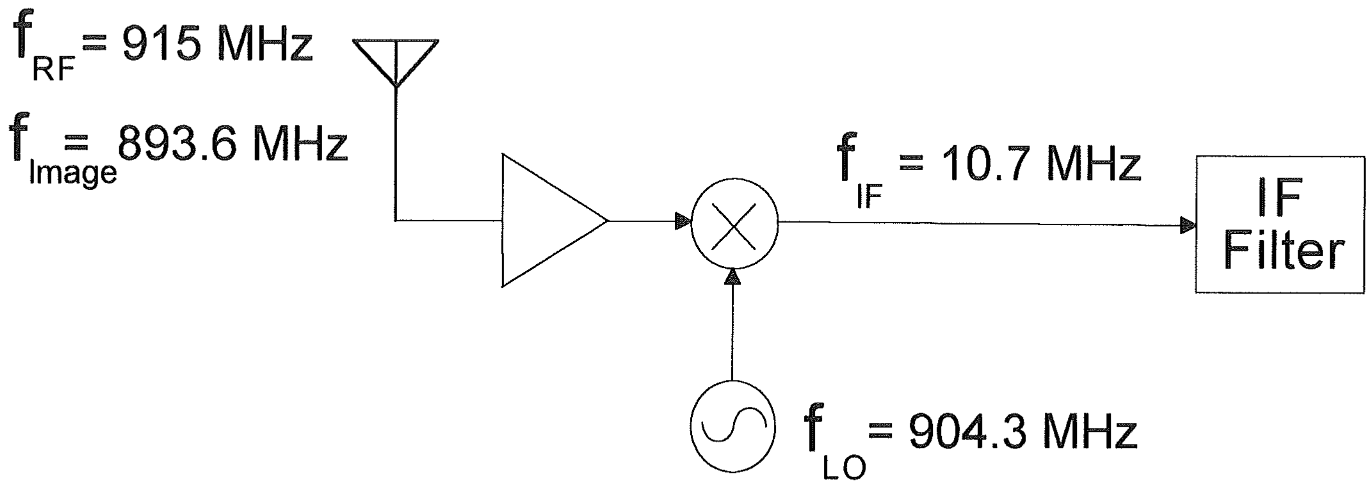
Amplification at two different frequencies

Easier to get high gain at lower intermediate frequency

Tuned by changing LO frequency

Better selectivity (high-quality, fixed-tuned IF filter)

The Image Problem

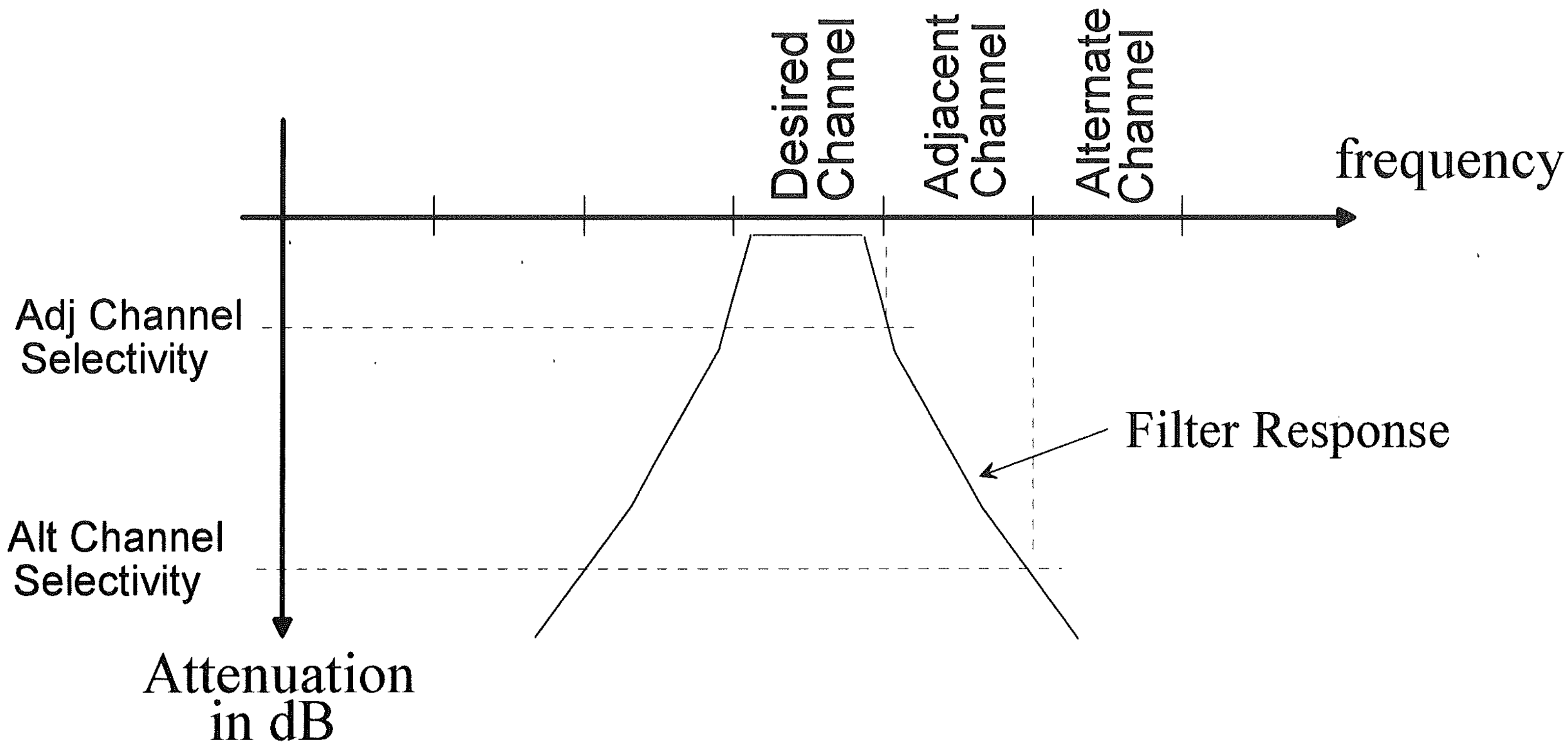


Problem: 915 and 893.6 MHz both produce 10.7 MHz when mixed with 904.3 MHz

Solution: Filter out image frequency before mixer (or use "image reject" mixer)

Image Rejection: Amount that image frequency is attenuated

Selectivity

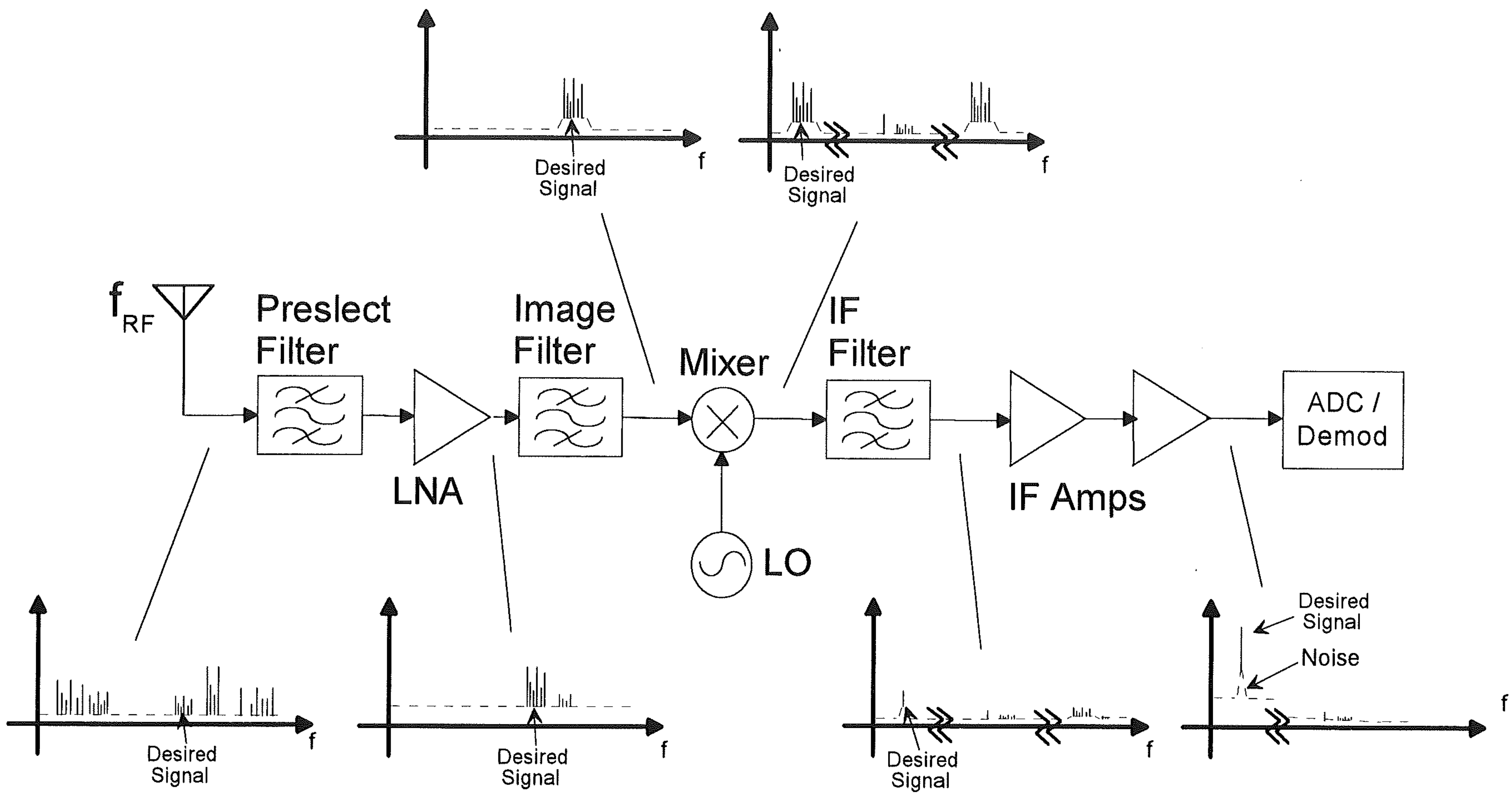


NOTES:

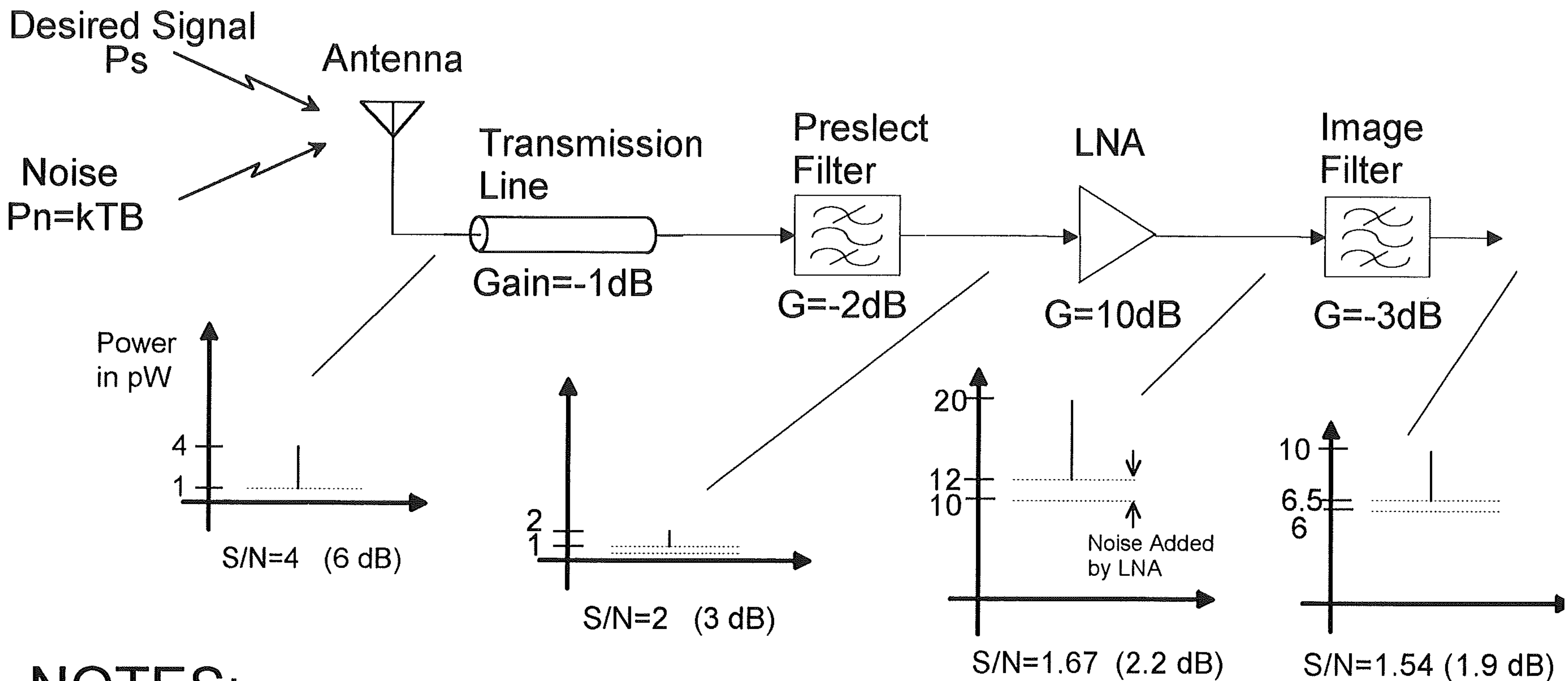
Typical adj chan selectivity = 20 dB, alt chan selectivity = 60 dB

Adjacent channel may not be used in same geographic area
or, "guard bands" may be used at edges of channels

Modern Superhet Design



Weak Signal Performance



NOTES:

Losses before LNA degrade S/N and sensitivity significantly
LNA amplifies signal above noise floor (adding some noise)
Later losses produce (ideally) little additional degradation

Noise Figure

Degradation in S/N and receiver sensitivity is quantified by

"Noise Factor" F and "Noise Figure" (NF):

$$F \equiv \frac{S/N\ @\ input}{S/N\ @\ output} \qquad NF \equiv 10\log(F)\ \text{dB}$$

Applications:

$$S/N\ @\ output = \frac{S/N\ @\ input}{F} \text{ or in dB, } S/N\ @\ output = S/N\ @\ input - NF$$

$$Rcvr\ sensitivity = Ideal\ sensitivity + Rcvr\ NF$$

Typical "Good" values range from 1 to 6 dB for LNA and 1 to 8 dB for receiver as a whole.

Noise Figure Evaluations

Passive Components (tr-line, filter, etc.)

$$F = \frac{S/N\ @\ input}{S/N\ @\ output} = \frac{S_{in}}{S_{out}}\frac{N_{out}}{N_{in}} = \frac{S_{in}}{S_{out}} = \frac{1}{Gain} \quad \rightarrow \quad NF = InsertionLoss(dB)$$

Active Components (LNA, active mixer, etc.)

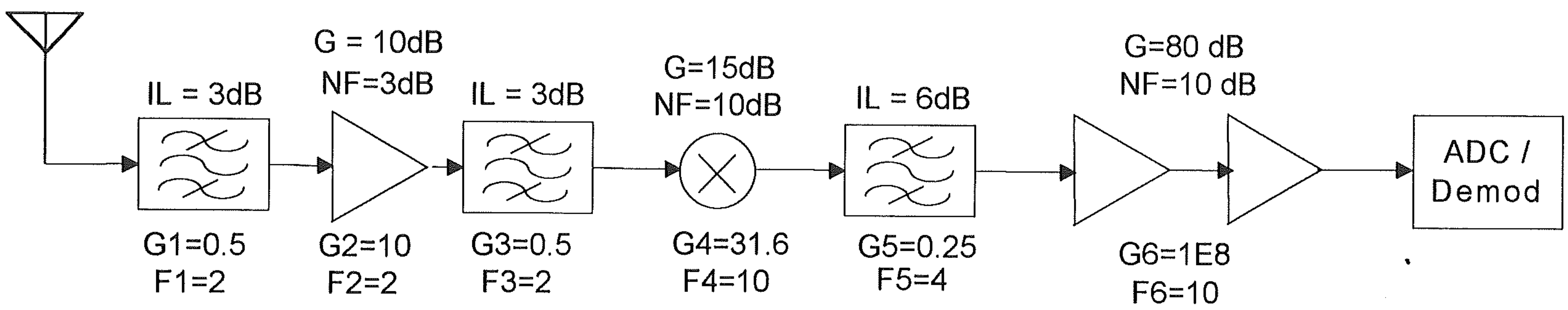
$$F = \frac{S/N\ @\ input}{S/N\ @\ output} = \frac{S_{in}}{S_{out}}\frac{N_{out}}{N_{in}} = \frac{1}{Gain}\frac{(Gain)(N_{in})+N_{out\_excess}}{N_{in}} = 1 + \frac{N_{out\_excess}}{(Gain)N_{in}}$$

NOTES:

For good LNA, $N_{out\_excess} < (Gain)(N_{in})$, so F < 2 (NF < 3 dB)

For mixer, situation is more complex. See lecture on mixers.

Receiver System Noise Figure



$$F_{rcvr} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \frac{F_5 - 1}{G_1 \ldots G_4} + \frac{F_6 - 1}{G_1 \ldots G_5}$$

$$= 2 + 2 + 0.2 + 3.6 + 0.04 + 0.46$$

$$= 8.3 \quad => \quad NF = 9.2 \text{ dB}$$

NOTE:

Losses ahead of LNA hurt noise figure

LNA gain in this design is low, leading to big hit from mixer

Additional Notes on Noise Figure

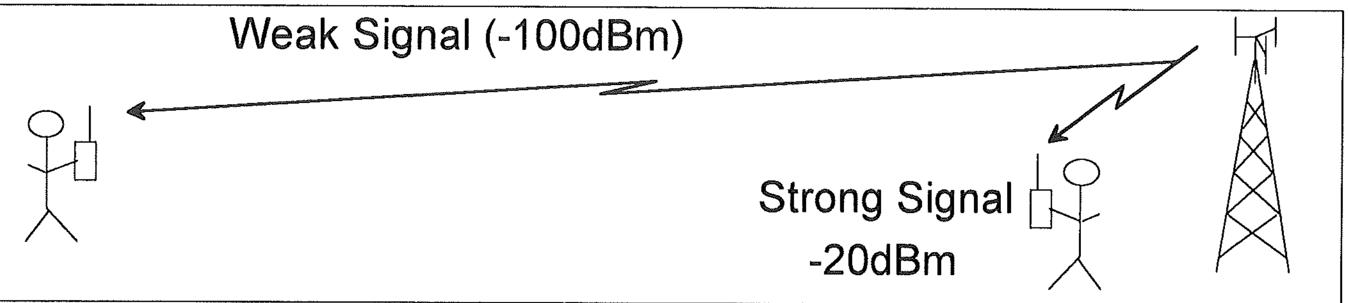
- Noise Figure usually assumes $N_{in} = kT_oB$ with $T_o = 290$ K (This is called "Standard Noise Figure")
- Standard Noise Figure works well for terrestrial links, but is not appropriate for satellite receivers with directional antennas where $T_A \neq 290K$.
- For satellite receivers, use "Operational Noise Figure" F_{op} which assumes $N_{in} = kT_AB$, (where T_A may be 30 to 100 Kelvin).
- F_{op} for receiver can be found from F for receiver from:

$$F_{op} = 1 + (F - 1)\frac{T_o}{T_A}$$

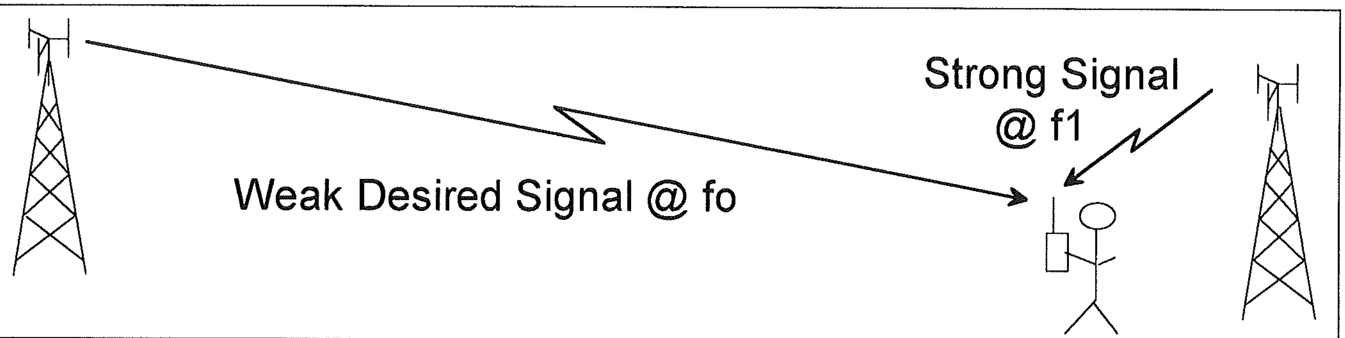
- For satellite receivers, "Noise Temperature" is often used in place of noise figure. (See references)

Strong Signal Performance

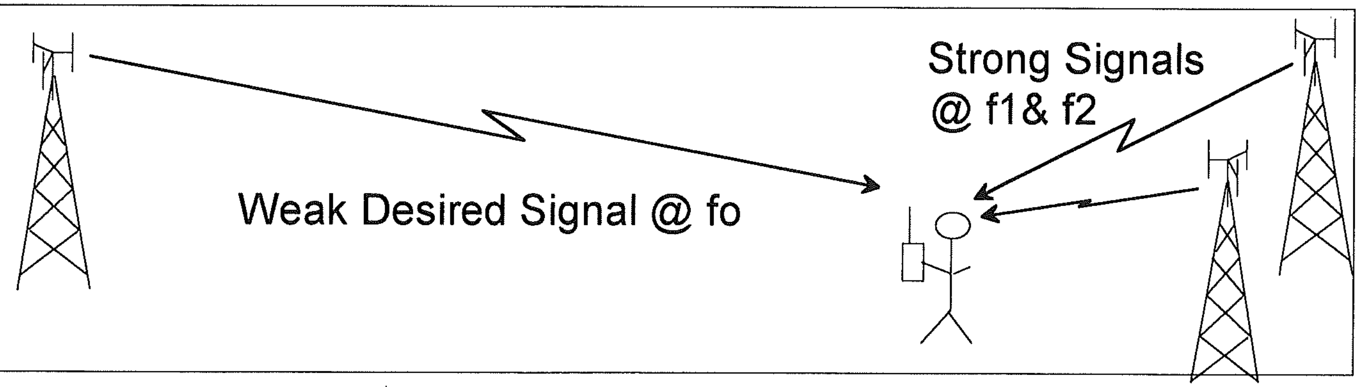
Basic Dynamic Range Problem



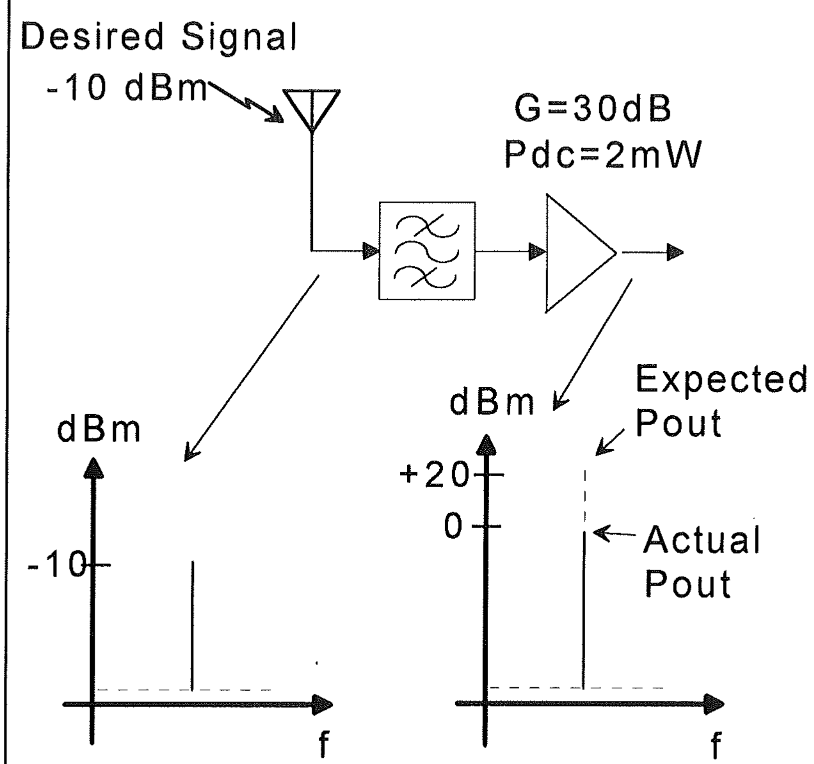
Blocking Dynamic Range Problem



Intermod Dynamic Range Problem



Basic Dynamic Range Problem



Effects

- Loss of amplitude modulation
- Distortion of phase

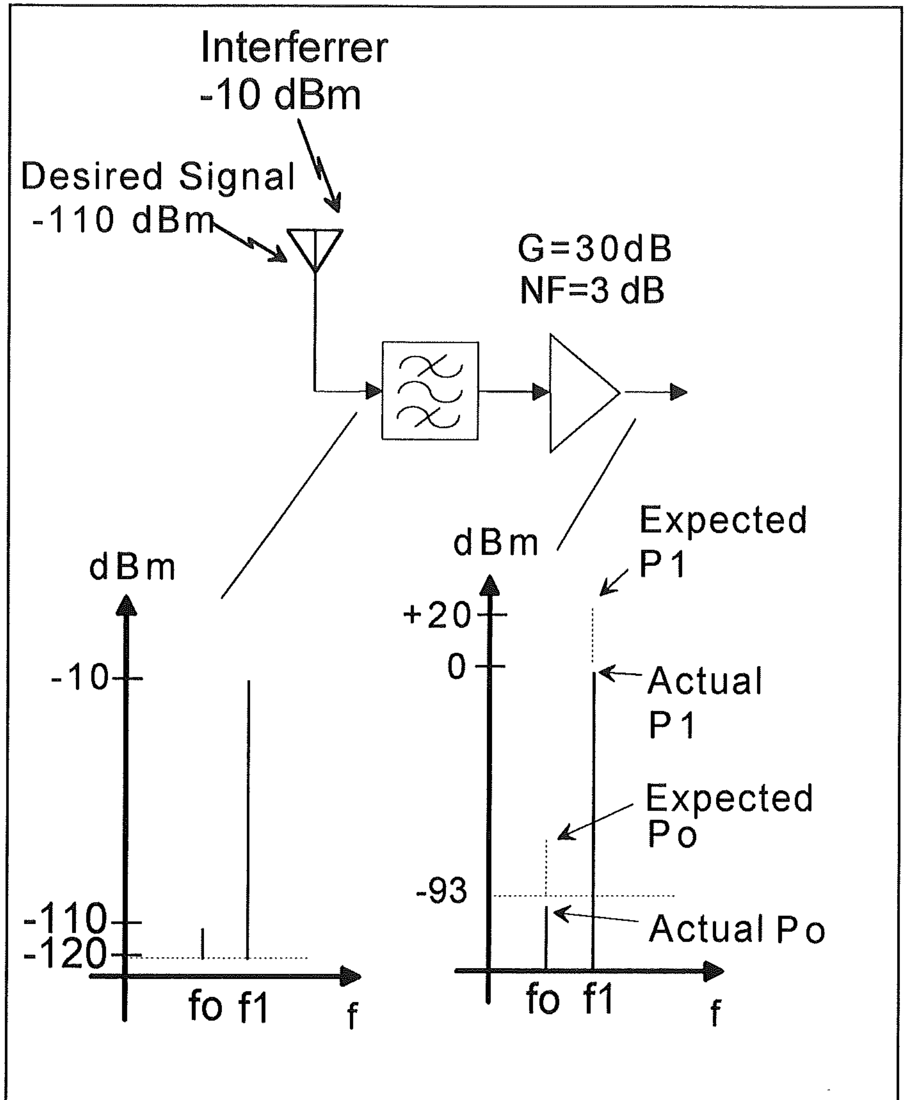
Solutions

- Use higher power LNA
- Decrease LNA gain
- Use FM/FSK modulation

NOTE

- Could occur in later stages also

Blocking Problem



Effects

- Gain compression in LNA
- Desired signal below noise floor at output

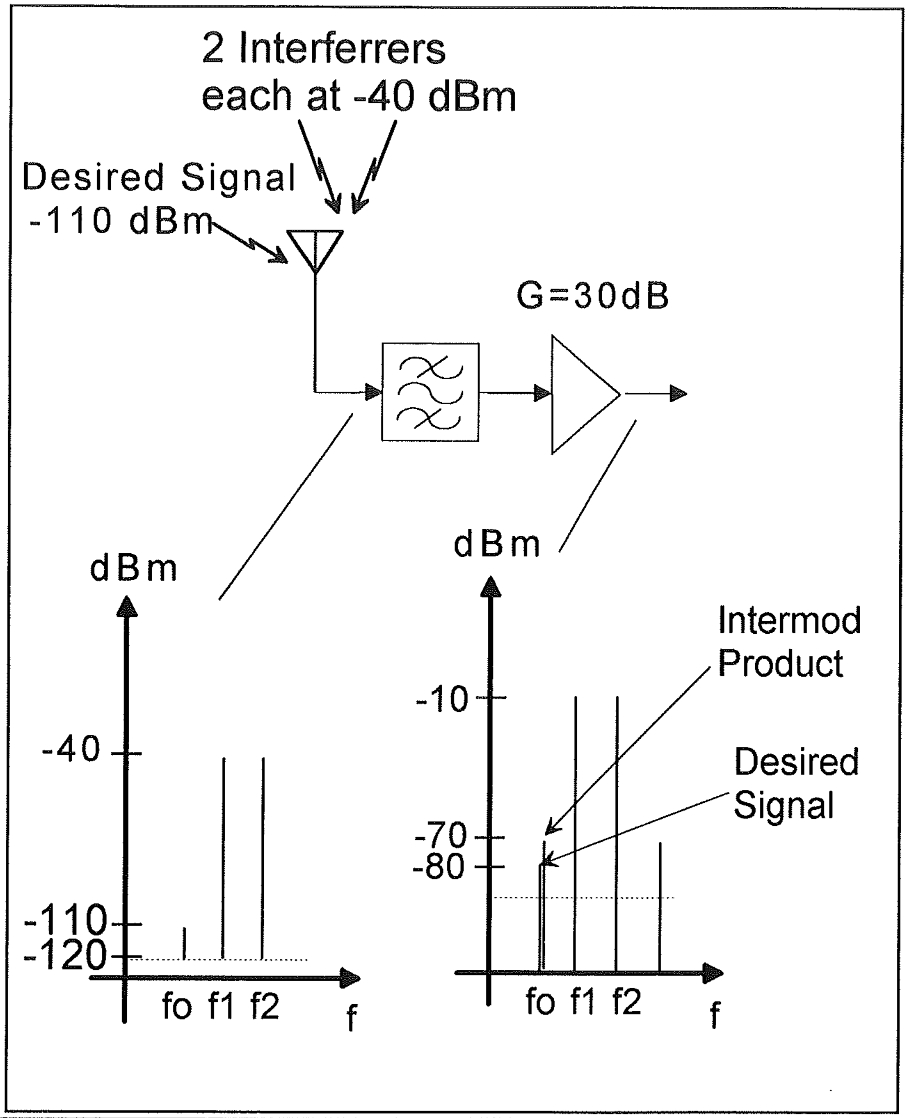
Solutions

- Use higher power LNA
- Decrease LNA gain
- Filter out f1 before LNA

NOTE

- Could occur in later stages also

Intermod Problem



Effects

LNA generates "intermod products" at 2f2-f1 & 2f1-f2.
Product at 2f1-f2 = fo overpowers desired signal.

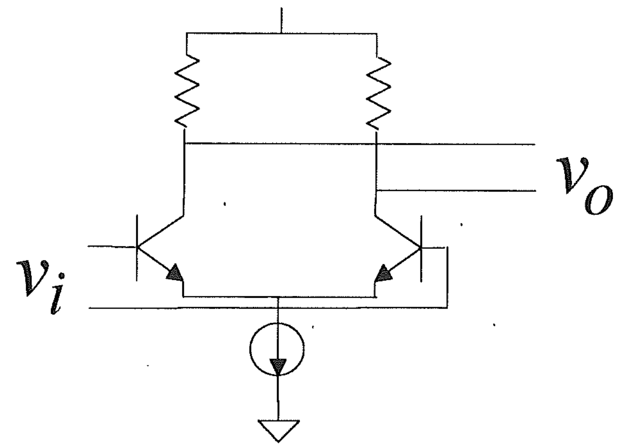
Solutions

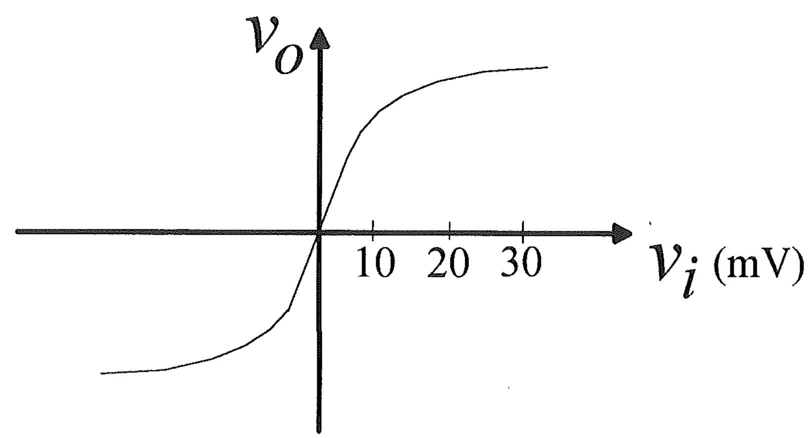
Use higher power LNA.
Decrease LNA gain.
Filter out f1, f2 before LNA.

NOTE

Could occur in later stages also (especially mixer.)

Large Signal Circuit Analysis





Expand v_o vs v_i in a Maclaurin series:

$$v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + \ldots$$

Small Signal Output Non-Linear Distortion Terms

Single-Tone Case

Let $v_i = V\cos(\omega_o t)$

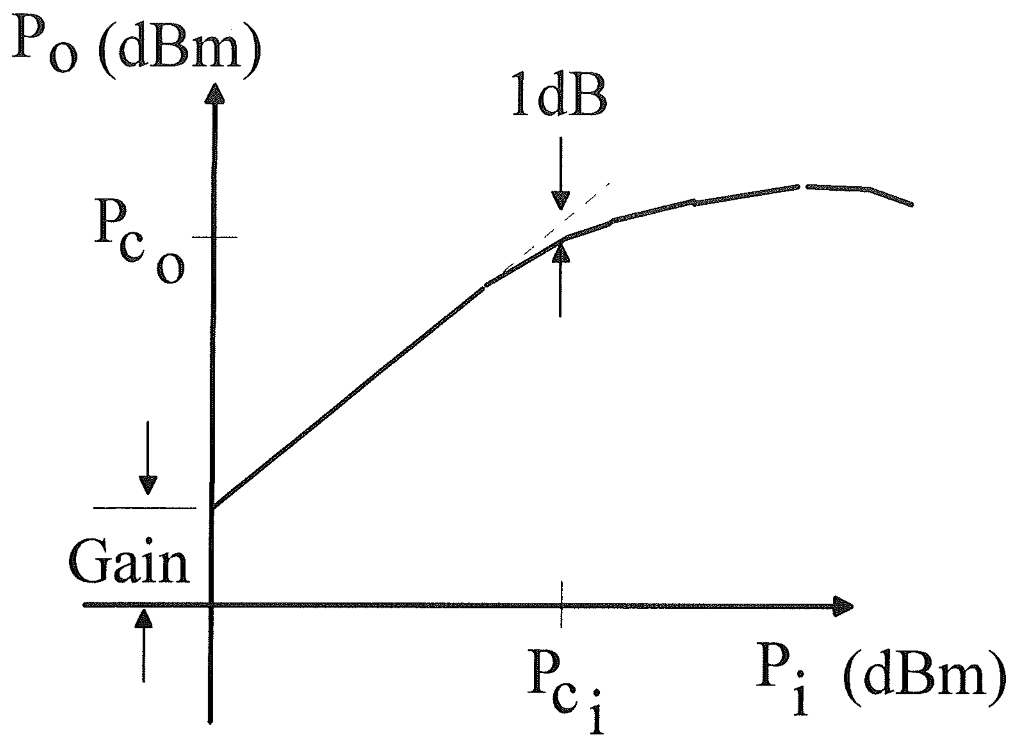
Then:

$$v_o = A_1 v_i + A_2 v_i^2 + A_3 v_i^3 + \ldots$$

$= A_1 V\cos(\omega_o t) +$	Expected small signal output +
$\frac{A_2}{2} V^2[1 + \cos(2\omega_o t)] +$	Rectification + 2nd harmonic +
$\frac{A_3}{4} V^3[3\cos(\omega_o t) + \cos(3\omega_o t)] +$	Gain compression* + 3rd harm +
...	Additional harmonics, etc.

*Assuming $A_3 < 0$

1dB Compression Points



Plot of fundamental frequency output power vs input tone power

NOTE

P_{c_o} is typically 0.1 to 0.5 of DC power consumption

$P_{c_i} = P_{c_o}$ - Gain (in dB, dBm units)

Two-Tone Case

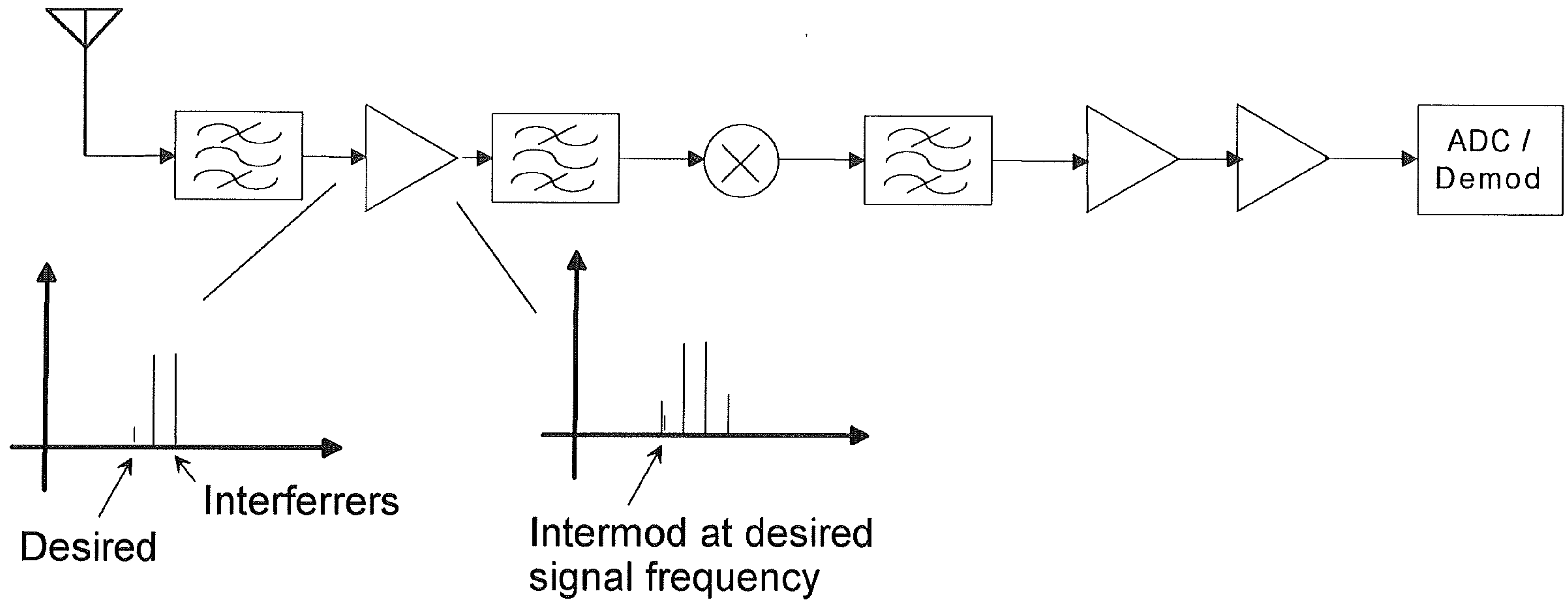
$$\text{Let} \quad v_i = V\cos(\omega_1\, t) + V\cos(\omega_2\, t)$$

Then:

$$v_o = A_1\, v_i \;+\; A_2\, v_i^2 \;+\; A_3\, v_i^3 + \;\ldots$$

$$\begin{aligned}
&= A_1[V\cos(\omega_1\, t) + V\cos(\omega_2\, t)] + \\
&\quad \textit{DC offset and harmonic terms} + \\
&\quad (const)(V^3)[\cos((2\omega_1 - \omega_2)t) + \cos((2\omega_2 - \omega_1)t)] + \\
&\quad \textit{higher order terms}
\end{aligned}$$

The Intermod Problem



Can occur in any circuits up to last IF filter.
Typically occurs at lower power than blocking problems.
Can be mitigated with good preselect filters if interferrers are out-of-band
Cannot be filtered if interferrers are close to desired signal frequency .
Requires higher power LNA, mixer, etc.

Quantifying Intermod Products

For two-tone input:

$$v_i = V\cos(\omega_1 t) + V\cos(\omega_2 t)$$

$$v_o = A_1 V\ [\cos(\omega_1 t) + \cos(\omega_2 t)]\ +$$

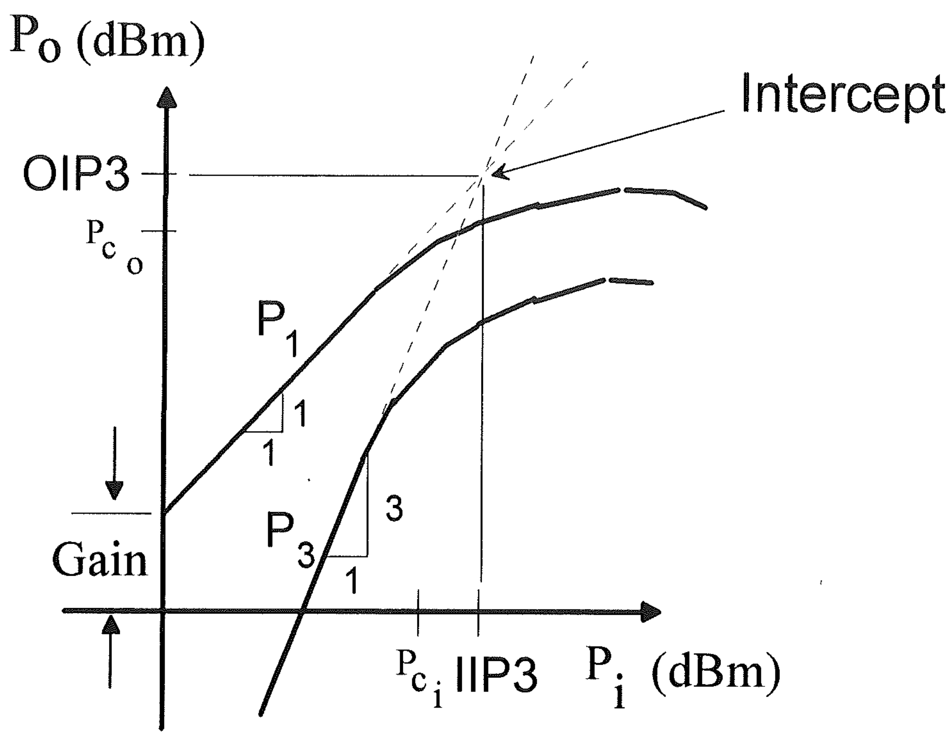
$$(const)\,(V^3)\,[\cos((2\omega_1 - \omega_2)t) + \cos((2\omega_2 - \omega_1)t)]\ +$$

additional terms

Component of Output	***Voltage at Output***	***Power at Output***
"Desired" Signals	$V_{o1} = A_1 V$	$P_{o1} = P_i + const$
Intermods	$V_{o3} = (const) V^3$	$P_{o3} = 3P_i + const$

NOTE: P_{o3} (power in third-order products) increases 3 times faster than P_{o1} (power in input signals).

Third Order Intercept Points



Plot P1 and P3 versus Pi at low Pi

Extrapolate to find intercept

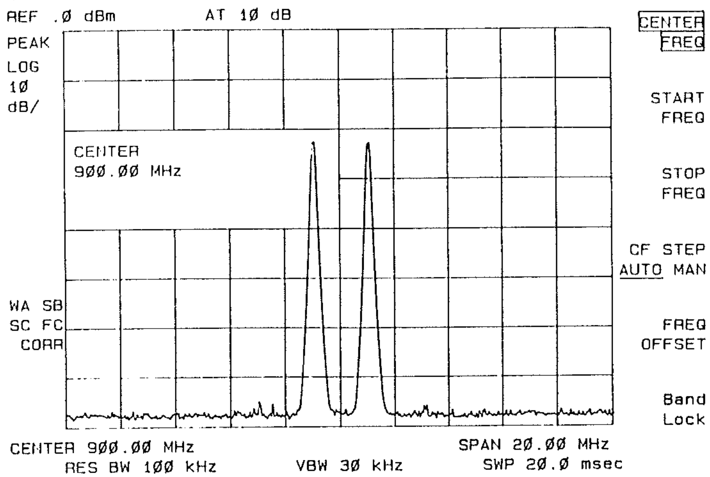
Note that
IIP3 = OIP3 - Gain

OIP3 often spec'd since it is higher !!

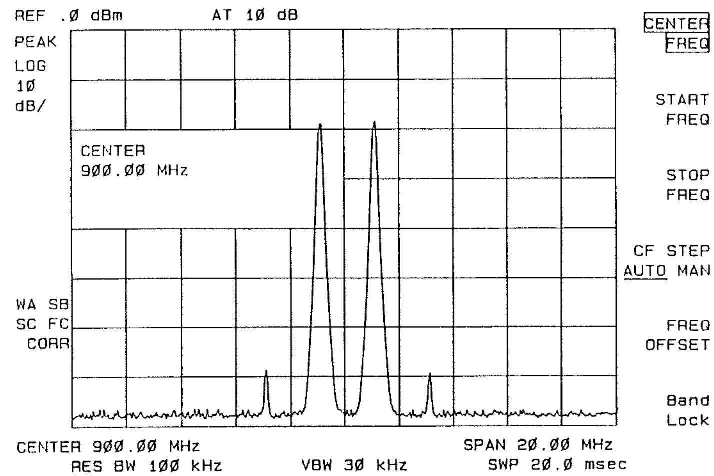
IIP3 is called the "3rd order Input Intercept Point"

OIP3 is called the "3rd order Output Intercept Point"

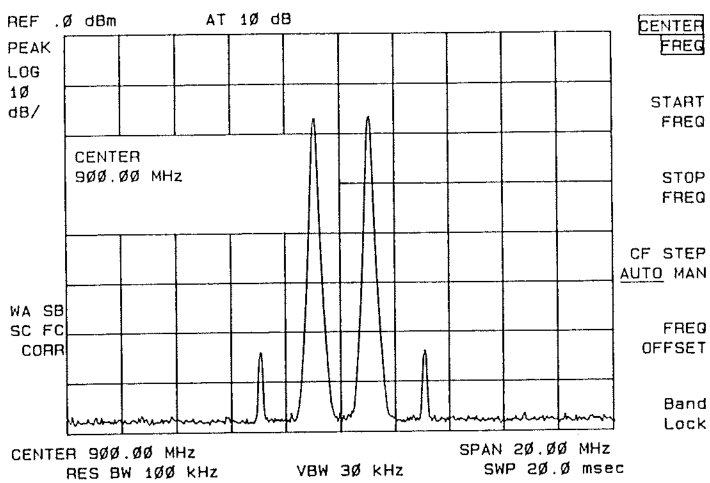
Spectrum Analyzer Displays



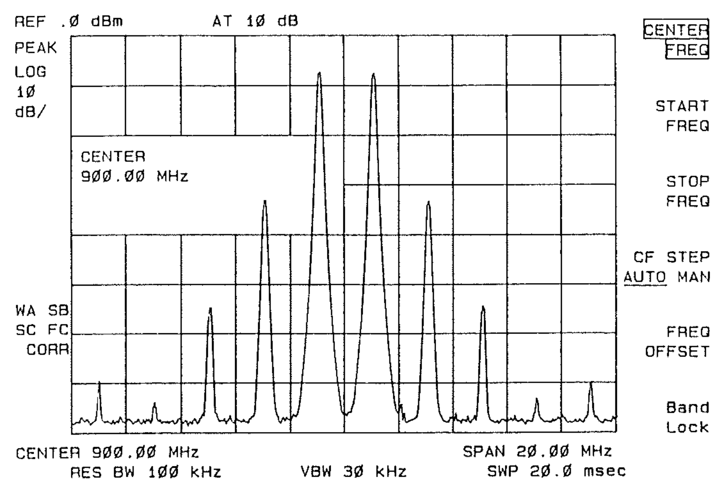
Low Pi. Intermods at noise floor



Increased Pi. Intermods above noise.

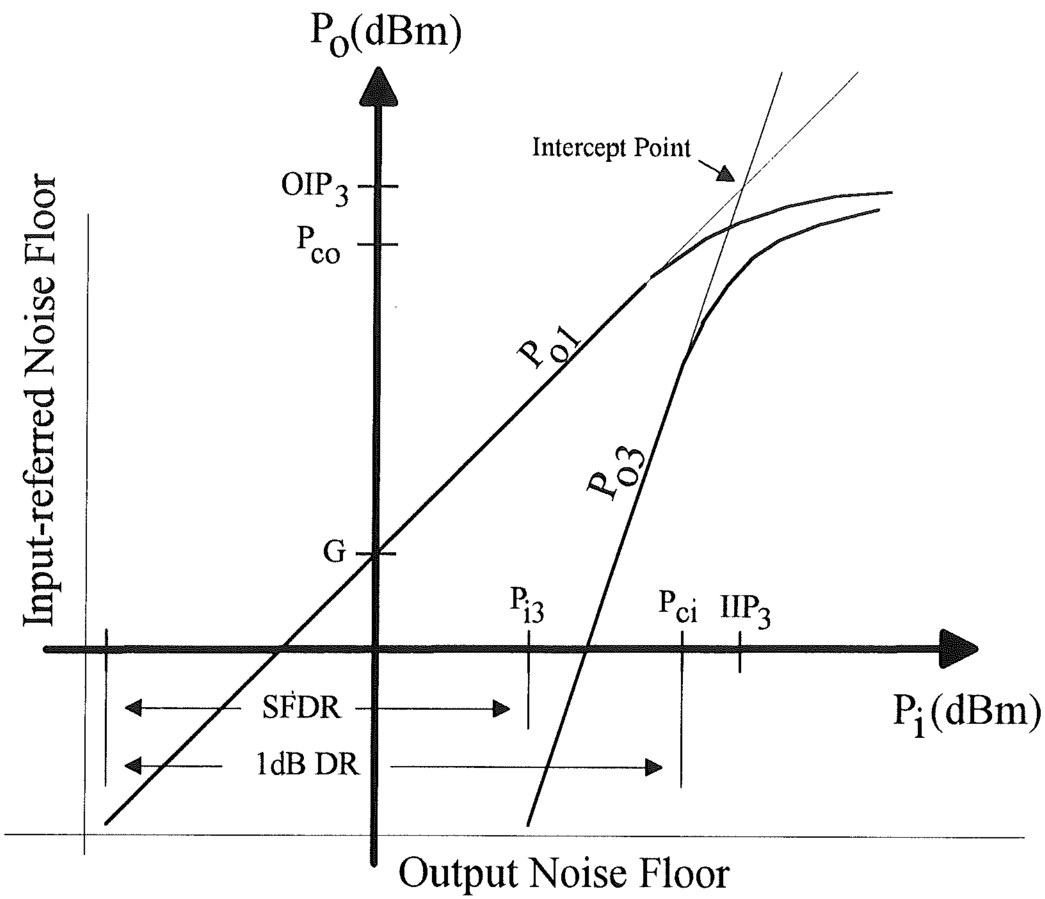


Pi increased by 2 dB. Intermods by 6dB.



High Pi. Higher order products present.

Dynamic Range

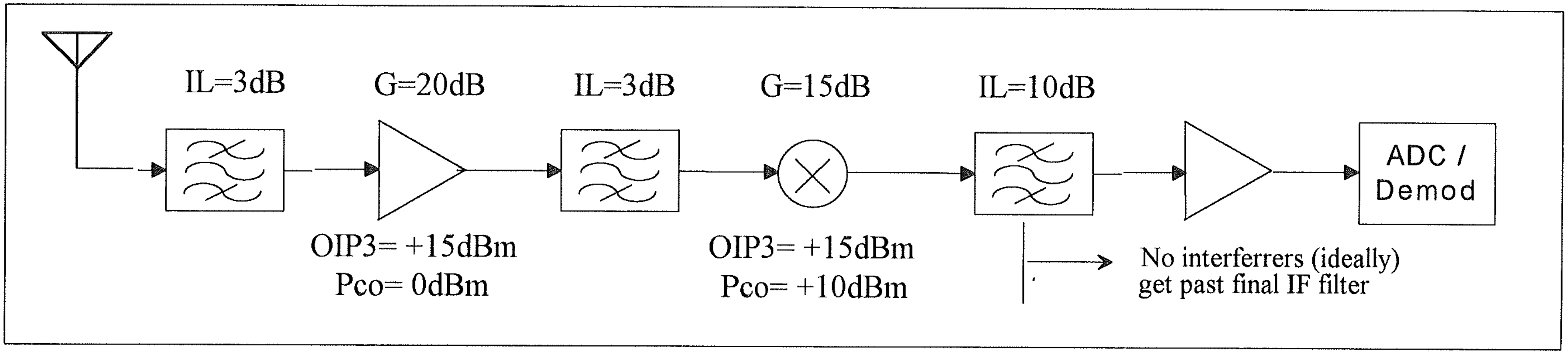


At input power P_{i3} , 3rd order products fall below noise floor. Difference of this and receiver sensitivity is "Spurious Free Dynamic Range" (SFDR)

1dB compression dynamic range uses compression point (Pc) as maximum level and is higher than SFDR.

Total dynamic range (using maximum acceptable input signal) may be significantly higher than both, since compression is acceptable in FM/FSK systems.

Estimating Receiver IIP3 & P_{ci}



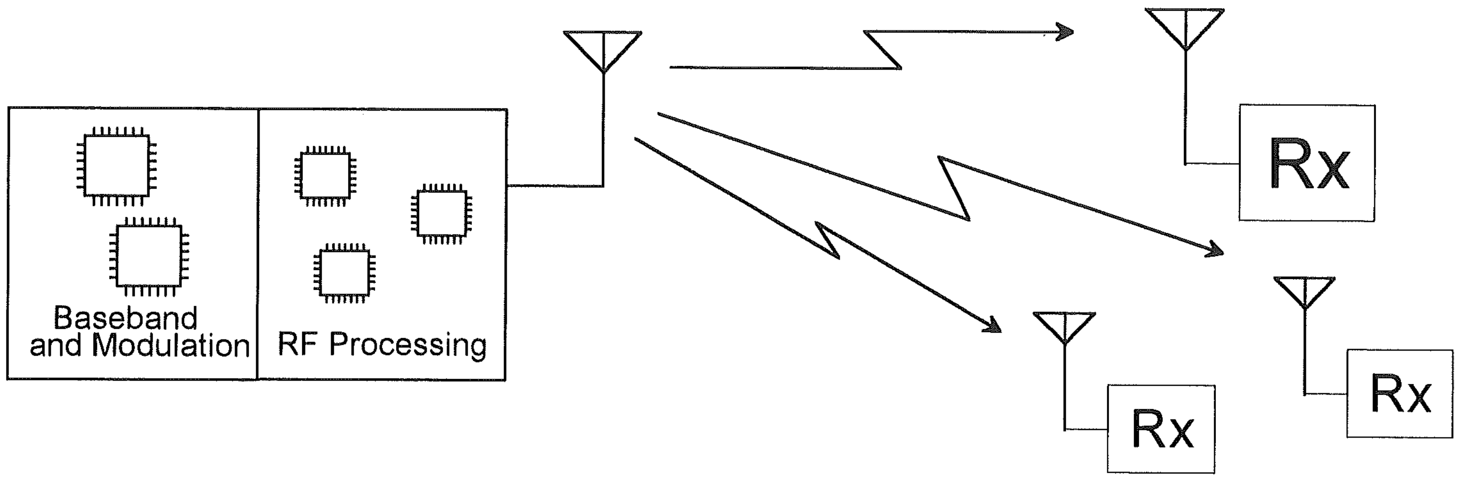
Component	Pco	OIP3	Cumulative Gain (Gc)	Pci = Pco - Gc	IIP3 = OIP3 - Gc
Preselect Filter	-	-	-3	-	-
LNA	0	15	17	-17	-2
Image Filter	-	-	14	-	-
Mixer	10	15	29	-19	-14

Overall receiver Pci ≈ -19 dBm (limited by mixer)
Overall receiver IIP3 ≈ -14 dBm (limited by mixer)

Transmitter Performance Issues

- Basic Requirements
- Block Diagrams
- Frequency Stability
- Harmonic and Spurious Emissions

Basic Requirements



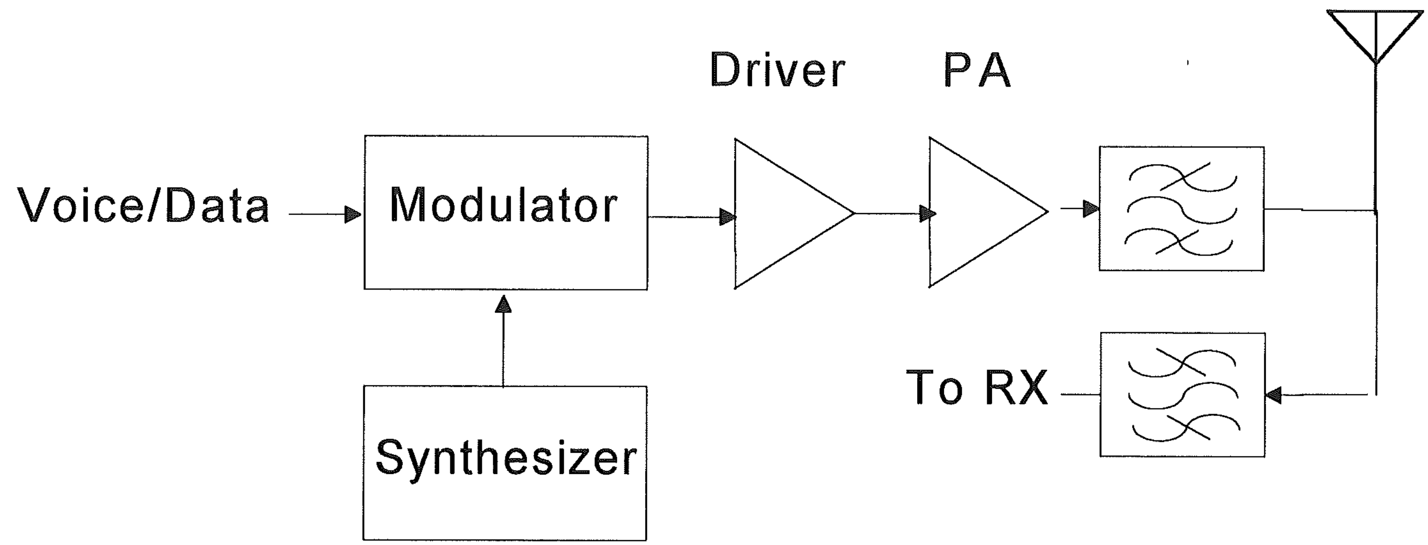
Generate RF output at proper frequency.

Amplify to desired power level.

Limit out-of-band / off-channel emissions.

Maximize efficiency to increase "talk time".

Typical Block Diagram



Frequency Stability

Example Requirements: (900 MHz AMPS cellular service)

Center frequency	824 - 849 MHz	=> Stability = +- 2.4 ppm over temperature!
Channel width	30 kHz	
Accuracy needed	+- 2 kHz	

(Less severe for wideband services)

Solutions:

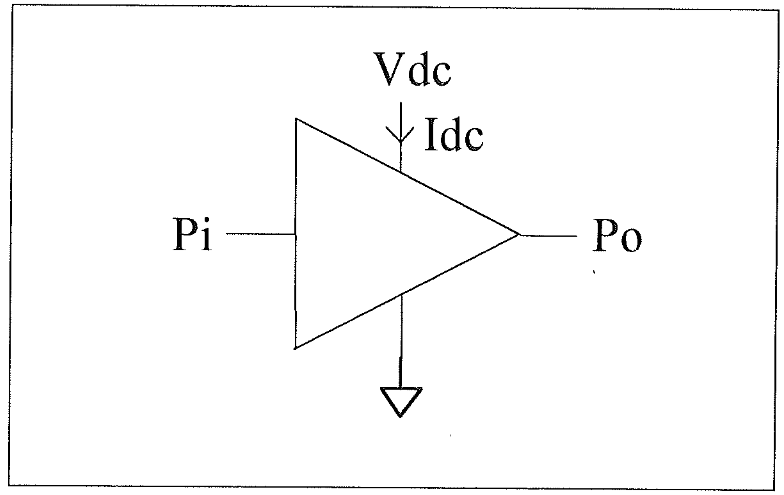
Crystal-controlled frequency synthesis
Temperature controlled/compensated crystal reference

Power Amplifier Basics

$$P_{dc} = V_{dc}\, I_{dc}$$

$$P_o = P_i\, G \lesssim P_{co} < P_{dc}$$

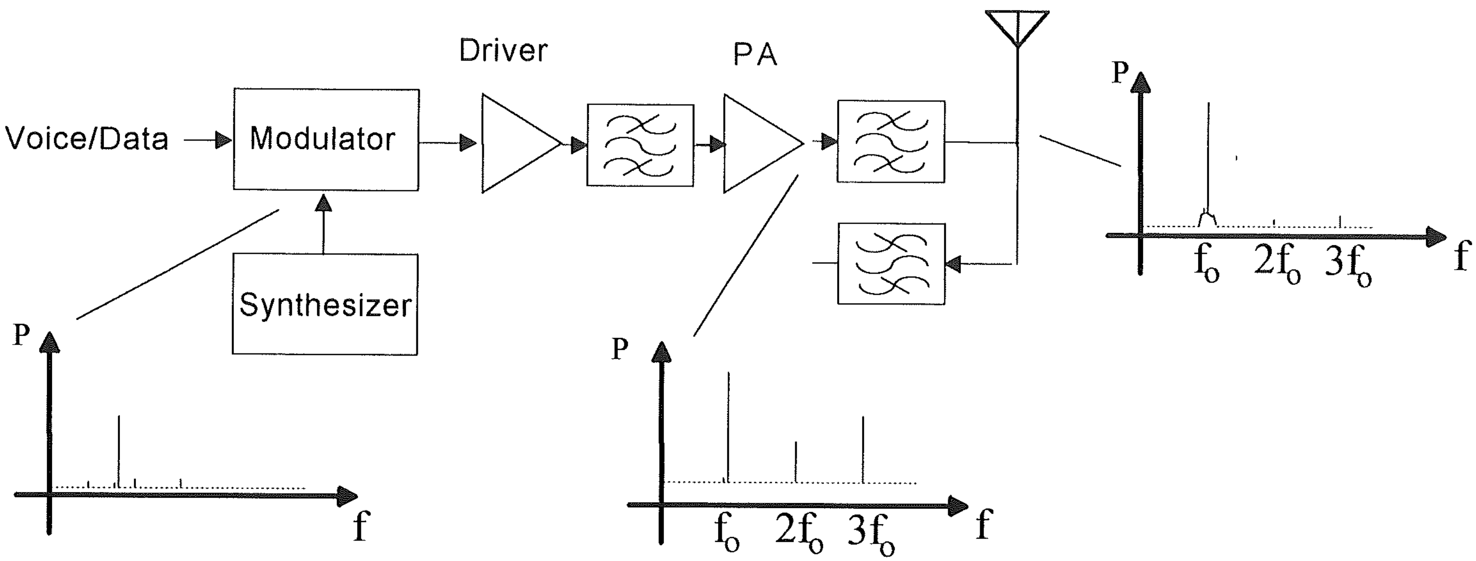
$$\text{Basic Efficiency} = \frac{P_o}{P_{dc}}$$



To Maximize Talk-Time:

Run P_o close to output compression point P_{co}
Design PA for high efficiency
Limit P_o to that needed for communication (power control)

Harmonic / Spurious Emissions

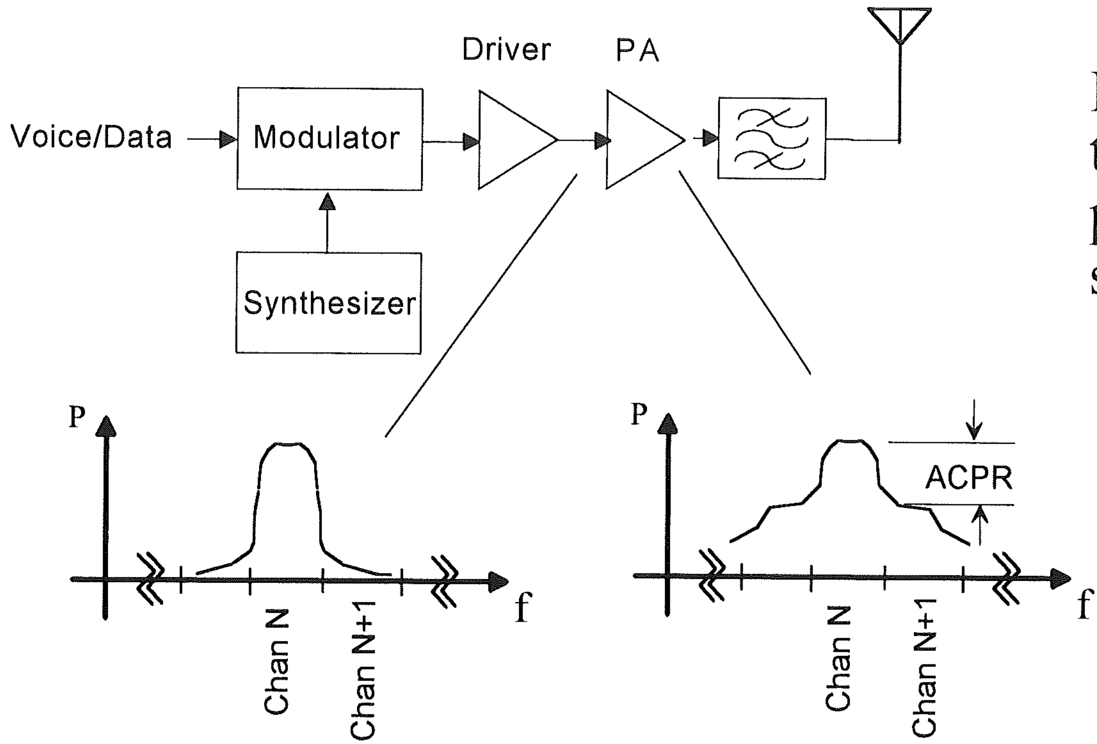


Minimize/filter synthesizer and modulator spurious outputs

Filter PA output to attenuate harmonics and out-of-band noise

Harmonics and spurious are often spec'ed in terms of "dBc" (dB relative to carrier)

Spectral Regrowth and ACPR



PA running close to compression point spreads spectrum

Adjacent Channel Power Ratio (ACPR) gives ratio of power in adj and desired channels

Solutions:

Back off Po in PA relative to compression point.
Design modulation to minimize spectral regrowth.
Do not use adjacent channels in same cell.

For More Information ...

- W. B. Kuhn, *Design of Integrated, Low Power, Radio Receivers in BiCMOS Technologies,* Ph.D dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA, 1995. (Available free through VT On-line thesis and dissertation project. Go to www-personal.ksu.edu/~wkuhn/dissertation.html or http://scholar.lib.vt.edu/theses)
- B. Razavi, *RF Microelectronics,* Prentice Hall PTR, 1998.
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- T. H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*, Cambridge University Press, UK, 1998.
- K. Hansen, "Wireless Communications Devices and Technology: Future Directions," Proc. IEEE Radio Frequency Integrated Circuits (RFIC) Symposium, pp. 1-6, 1998.
- J. B. Hagen, *Radio-Frequency Electronics - Circuits and Applications*, Cambridge University Press, UK, 1996.
- American Radio Relay League, *The ARRL Handbook,* 1998.
- Various data sheets and application notes on RFICs available on the web.